THE OPERATION AND DESIGN OF SPARKING PLUGS.

Paper read before the Coventry Graduates Section.

THE OPERATION AND DESIGN OF SPARKING PLUGS.

By H. WARREN.

Introduction.

The study of the development of the internal combustion engine, from its embryonic stages to its present state, is fascinating in the extreme, not only on account of the far-reaching commercial significance of the engineering achievements which have rendered progress possible, but also because each step forward, involving high temperatures, pressures and speeds, has been an advance achieved only by maintaining extraordinary mechanical perfection of design and manufacture, even in the face of some theoretical impossibilities.

The actual ignition of the explosive charge in the engine cylinder is one of the predominant essentials, and it is this particular phase of the subject with which the author proposes to deal, confining his remarks to the physical conditions under which ignition is effected, and the operation and design of sparking plugs.

Although a considerable amount of information concerning the working of plugs may be found in various articles which have appeared in the technical press, so far as the author is aware, no paper has been written co-relating the physical, electrical and chemical aspects of operation and design, and dealing specifically with the subject of sparking plugs. It is this fact which has encouraged him to write the present paper, and which is offered in excuse for a certain amount of detail that has been introduced in order to render the paper complete, rather than on account of its originality.

The statement that the plug is the weakest point in the internal combustion engine has often appeared in print, and though there are, undoubtedly, grounds for this assertion, credit must be given to the manufacturers for very rapid progress in design made during the last few years.

In the very early days of the industry flame ignition was used, but this was only effective for igniting up to four or five charges per second, and the incandescent tubes of porcelain, iron, nickel and incandescent platinum wire also found their adherents. The catalytic action of spongy platinum was later applied, but all these devices have been practically abandoned in favour of the electrical ignition proposed in 1799 by Lebon.

It is of interest to note that the first plug appears to have been produced by Lenoir in 1855. Low tension mechanical plugs were devised, and special mention should be made in passing of the Bosch "Honold" magnetic plug, which was used in conjunction with low-speed single cylinder stationary gas engines. In this interesting plug the low tension magneto ignition current was led through the coils of an electro magnet enclosed in the body of the plug, which rocked the insulated electrode and separated it from the earthed electrode, thus drawing out an arc between the contacts. As soon as the arc died out a spring returned the insulated electrode to its original position in contact with the earthed electrode. As a matter of interest a diagrammatic representation of this plug is given in Fig. 1.

Low tension ignition, so far as automobile and aircraft engines are concerned, has now been entirely superseded by high tension ignition, and the high tension plug, as used in car and aeroplane engines, will be dealt with in detail in this paper.

The sparking plug, although the smallest unit of the engine, performs an indispensable function while operating under the most adverse conditions; its design and manufacture call for the combined skill of the automobile and the electrical engineer, and also that of the chemist in the matter of insulators.

The subject will be divided under the following eight general headings:—

1. The Ignition of the Charge.
2. Operating Conditions.
3. The Ideal Plug.
4. The Electrodes.
5. Insulators.
6. The Problem of Gas Tightness.
7. Special Plugs.
8. Problems still Requiring Attention.

(1) The Ignition of the Charge.

(a) *The Process of Ignition.*—The problem of elucidating the actual process of ignition of the explosive mixture in the combustion chamber, is a subject which calls for the utmost ingenuity of the chemist and the physicist. The fuel possesses potential energy, which, by its combustion under favourable conditions, is converted into work; the designers and manufacturers of ignition

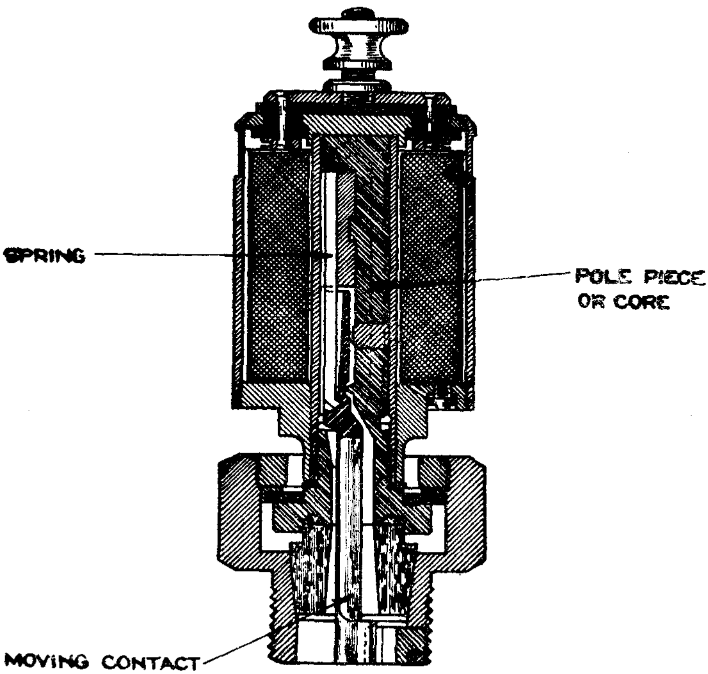


Fig. 1.—Bosch Magnetic Plug.

apparatus, equally as much as the engine builders, are concerned in effecting this transformation in the most efficient manner.

Satisfactory ignition depends upon good carburation, a reliable source of high tension current, and suitable plugs. It is also assisted by the turbulence of the charge in the cylinder, as the actual combustion proceeds rather slowly in the initial stage, but the rate increases very rapidly as the igniting surface enlarges. It seems that there can be no definite ignition temperature except under very exactly defined conditions, and in this connection it is interesting to recall Professor Morgan's reference to the manifestly low temperature of a manure heap, which may, nevertheless, be in a state of combustion.

Whether the initial ignition by the spark is of ionic or thermal origin is a matter upon which authorities differ, but the author suggests that the action is generally a combination of both of these effects, together with the mechanically disruptive action, always associated with the passage of an electric spark. It seems that immediately before the spark occurs, the ionization of the gas between the plug points must be pre-supposed; this renders the passage of the spark possible, and in its career to the earthed electrode it dissipates heat and buffets the medium, thus bringing its temperature to the ignition point.

Whatever may be the true explanation of the inception of the ignition, it is clear that the spark is the starting point of a wave of compression, and the plug designer is responsible for the introduction of this spark into the combustion chamber, in such a way that the compression of the engine is unaffected, and that the maximum advantage is taken of the incendiary characteristics of the spark so carefully nurtured by the magneto makers.

(b) *Ignition by Condenser Discharge.*—With the above outlined conditions in mind it is easy to see why the well-known Lodge system of ignition should yield good results, particularly with weak mixtures.

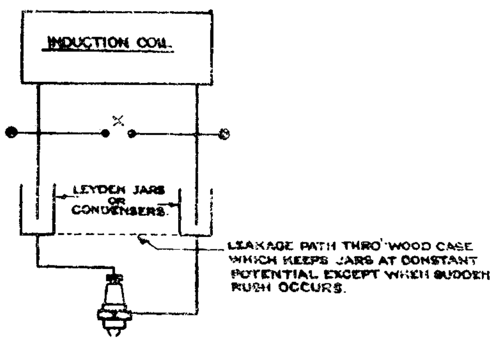
Briefly, the Lodge system is constituted of a source of high tension current which charges up a condenser till it overflows with a violent instantaneous rush, the connections being so arranged that the discharge occurs between the plug points. The details of the system are diagrammatically represented in Fig. 2. The plug insulation sustains no electrical strain until the moment that the condenser overflows, and then the sudden rush of the discharge has a tendency to dislodge any foul matter which may be clogging the plug points. Further, a high frequency current such as that produced by the Lodge system would not follow a slight leakage path between the plug electrode, but would leap the air gap with an instantaneous rush.

The duration of the spark, that is, the initial spark—because there are oscillations which follow—is extremely short, and it will be understood that this is a desirable feature, because with a given energy output the highest temperature will be produced by the spark which dissipates its heat in the shortest time, and a rapid local temperature rise means a correspondingly sudden local compression, favouring a more certain and rapid flame propagation.

Another high frequency system which has found a certain limited application in America is known as the Hi-Fre-Co. System. Considerations of space prevent more than a reference to the "Horseless Age," dated February the 10th, 1915, for details of this system.

The exceedingly short duration of the Lodge spark, and the correspondingly rapid velocity of the explosive wave, have also

LODGE SYSTEM OF IGNITION.



Jars are charged up from coil until they overflow and empty with a rush across "X" round the plug circuit.

FIG. 2.

another advantage in that they favour great precision of timing, which naturally leads to the mention of the jump-spark distributors which are now fitted in large numbers to the engines of aircraft. The resultant insulation of the secondary winding of the magneto from the insulated plug electrodes, until the moment of the passage of the spark, like the Lodge ignition, relieves the plug insulation of any strain up to the last moment, and the disruptive nature of the sudden spark has other points of advantage in common with the Lodge spark.

The advantage to be gained by using a spark of short duration is illustrated by the fact that a Polar Inductor Magneto, substituted for one of the usual type on a 200 h.p. engine resulted in an increase of speed of 30 to 50 revs. per minute. It is well known that Polar Inductor Magnetos yield sparks of short duration and that their high tension current curves present steep wave fronts.

(c) *Two-point and Double Ignition.*—The speed of propagation of the explosive wave depends, of course, very largely upon the composition of the charge, the compression, the temperature, and the cooling surface, but apart from this, it is quite obvious that if we have two favourably disposed starting points for the compression wave, the entire charge will be fired in a shorter time than would be the case with a single starting point. Indeed, it is claimed that under certain favourable conditions the time of rise of pressure is reduced by about one-third. Theoretically the maximum power would be developed if the charge could be instantaneously fired with the crank in the "dead centre" position, and it is with high speed racing engines and modern aircraft engines that the lag in the explosion is of most importance.

Looking at the matter from another view point, it will be seen that if the charge is fired in the minimum possible time the explosive pressure is a maximum, as the piston has not moved appreciably from the "dead centre" position and the volume of the combustion chamber is a minimum. This means high efficiency and fuel economy.

An unhomogeneous mixture may be imagined as introducing a kind of stagger into the motion of the explosive wave which naturally propagates most readily in the zones of most perfect mixture, and this is another source of loss of power which two-point ignition most probably does its share to minimise. Two-stroke engines are particularly liable to be working with imperfectly mixed gases, vitiated by the presence of residual exhaust gas.

To illustrate the familiar effect of two-point ignition, reference may be made to conclusive manograph records published by Dr. W. Watson as early as 1910 as a Cantor Lecture before the Royal Society of Arts, and two curves are shown in Fig. 3, which depict in a general way the advantage to be expected when using this ignition in favourable circumstances. It will be seen that not only is the maximum power obtainable with the two plugs operating greater than is the case with one, but also this maximum power is obtained with a smaller amount of spark advance. This latter feature is of particular interest if fixed ignition is used, as by suitable switches, arranged to use one or two-point firing at will, the effect of a two stage advance and retard is produced.

As a further illustration, a 500 cu. cm. single cylinder air-cooled engine, coupled to an electrical generator and running under

CURVES INDICATING IN A GENERAL MANNER THE EFFECT OF TWO-POINT IGNITION.

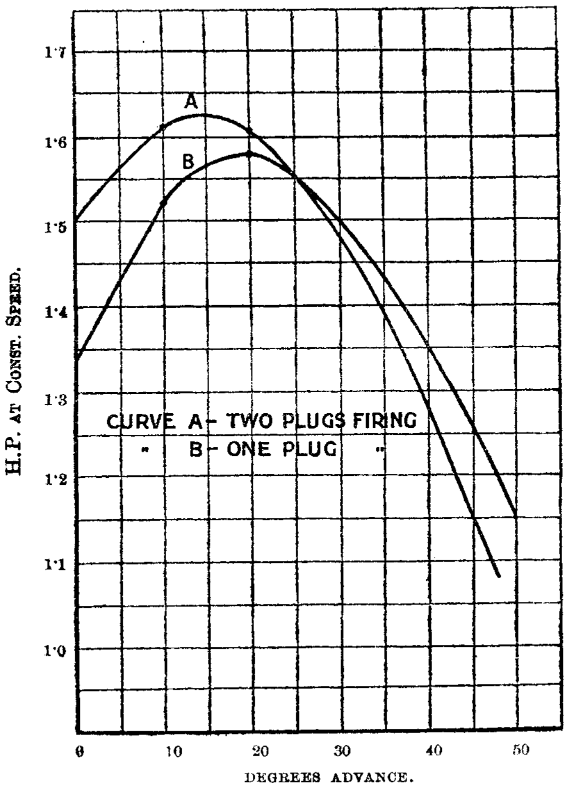


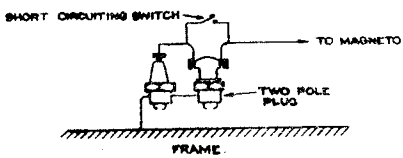
FIG. 3.

three-quarter load, was fitted with two plugs, one over the inlet valve and the other over the exhaust valve, and run at an over-load. An arrangement was provided (shown in Fig. 4) for firing from either one or both of the plugs, and the speed increased from 1,600 revs. per minute to 1,640 on simply changing from one to two-point ignition without in any way altering the other conditions. This may be regarded as quite a good performance, because the second plug over the exhaust valve must, by virtue of its location, have been considerably less effective than the other.

In testing certain 200 h.p. aeroplane engines fitted with two-point ignition, it is usually found that switching on the second set of plugs increases the revolutions about five per cent.

Apart from the question of increased power, two-point ignition ensures greater reliability, for, should one plug become sooted and short circuit, the spark will leap the gap between the electrodes of the other, and thus ignition will not fail. Multipoint ignition has its extreme devotees, for as many as four plugs per cylinder have been used in racing engines.

There is no doubt that many of the failures to detect the advantages of two-point ignition have been due to the second plug not



WIRING ARRANGEMENT IN TWO-POINT IGNITION TEST.

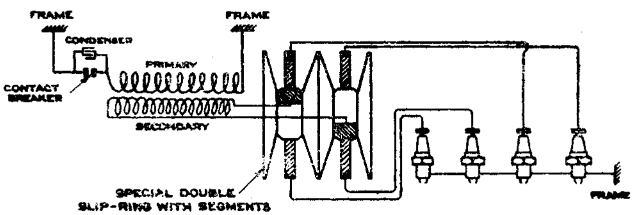
FIG. 4.

being placed in the most effective position in the cylinder, and when the plugs are not connected in series, a very slight divergence from synchronism might possibly be expected to result from the gaps of the two plugs not being of exactly the same magnitude.

The effects of two-point ignition would not be so marked in engines of very high compression, because of the high temperature to which the gases are raised, and the consequent approach to the Diesel conditions, which call for no applied ignition at all. In the Diesel cylinder the ignition must be imagined to occur spontaneously, the combustion starting at all points practically simultaneously.

Dr. Watson calls attention to another interesting effect of the plug being unfavourably situated. It is sometimes observed, when the combustion chamber is so formed as to favour resonance, that the spark causes a detonating wave, which produces the unpleasantly familiar "pinking" which sounds like hammer blows on the cylinder walls. This curious defect may usually be eliminated by altering the position of the plug.

Another system of ignition utilises two sparks per explosion, an active spark occurring in the firing cylinder and an inactive one in another cylinder, the piston of which is near the end of the exhaust stroke, and which contains, therefore, inert gas. This system, which involves the use of a special magneto, is diagrammatically illustrated in Fig. 5, where it will be seen that the two ends of the secondary are connected respectively to two segments insulated from the shaft and located as shown. Two sparks per revolution are produced, and a study of the connections will show how two plugs are always operated in series, the connection being through the frame. The effect is the same as single



Special Two-Spark Magneto Arrangement.

Fig. 5.

ignition, and the scheme is only adopted to cheapen the construction of the magneto.

There is yet another kind of double or dual ignition in which a plug carrying two separate pairs of electrodes is utilised. This enables two systems of ignition to be applied to an engine to which only one plug per cylinder can be fitted. A plug designed for this purpose is shown in Fig. 6.

(2) Operating Conditions.

The very rapid advances made recently in the development of high-speed and high-powered engines of the stationary and rotary type have given birth to plug conditions which call for quite special designs, and have raised entirely new problems for ignition engineers to solve.

The fundamental parts of a plug are three in number:—

(a) The threaded metal shell or body.

(b) The insulator or barrier.

(c) The insulated electrode.

There are no very special points of interest connected with the plug body, except the cylinder reach and the standardization of threads.

Only experienced drivers realise the effects of unsuitable plugs upon the power and flexibility of engines, and the fact that different engines require various designs of plugs is illustrated by the knowledge that some of the leading British plug manufacturers market

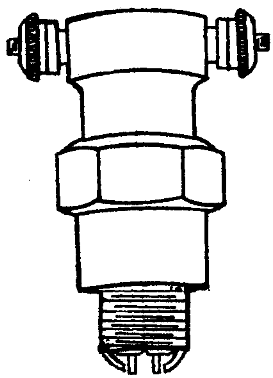


FIG. 6.

a score or more of plugs of different patterns, each being intended to meet the special conditions of particular engines.

To take a few examples:—

1. Heavy oil engines require plug electrodes and insulators adapted to the ready dripping off of oily deposits, and at the same time the electrode and insulators must be self-cleaning, but must not reach a sufficiently high temperature to cause pre-ignition of the charge.

2. American car engines which generally operate at comparatively low pressures and temperatures, present, therefore, not altogether unfavourable plug conditions in this respect; they are, however, rather oily, and addicted to carbon deposits, and special long insulator petticoats are therefore advisable.

3. Air-cooled motor-cycle engines give rise to rather high temperature work, and the too common alternate "over-oiling" and "starving" of the engines, as a result of the hand-fed lubrication, necessitates a plug which will persistently resist carbonising and short circuiting. Air-cooled engines always demand carefully selected plugs, as they are more sensitive in this respect than water-cooled engines. The front cylinders of motor-cycle twin-cylinder engines are often fairly innocent of excess lubrication, whereas the rear cylinders are sometimes the reverse, and accordingly the front plug is over-heated and the rear one is deluged in oil.

4. Two-stroke engines, in which ignitions occur with twice the usual rapidity, introduce very severe temperature conditions, and render advisable the fitting of radiating fins to the plugs.

5. Aeroplane engines require plugs, the reliability of which is of most vital importance, and service conditions are extremely severe, as aircraft engines run for very long periods on open throttle. In addition, rotary engine plugs are subjected to unusual stresses due to centrifugal force.

6. Aircraft and motor-cycle engines require plugs which are substantially weather-proof, so that the evils of external "cutting out" may be avoided.

7. Stationary gas engines are usually fitted with very large plugs, and this enables greater mechanical and electrical reliability to be attained. It is to be regretted that present standard engine design and universally accepted plug dimensions impose such restrictions on the size of the insulated electrodes and the insulators. Undoubtedly a more satisfactory article could be produced if these dimensional limitations were removed.

The author has no intention of intimating that plugs of present dimensions are unreliable, as it is very well known that several British makers produce many thousands of plugs annually of superlative quality, but the view is held that additional permissible mounting space could not fail to enable greater factors of mechanical and electrical safety to be provided. A recent patent covers the combination of the plug with the valve cap (Fig. 7), and this provides greater plug space, without altering the structural details of the engine.

In the author's opinion the more general fitting of air-cooled valve caps is to be encouraged, as this is another feature tending to reduce the severity of operating conditions.

(3) The Ideal Plug.

Sufficient has been written to indicate that no single plug design, however perfect, could meet the requirements of all engines and find favour with all users, and accordingly the author's draft of the requirements for an ideal plug must be sufficiently general to embrace the conditions appertaining to engines for cycles, cars, motor-boats, aircraft, etc. Broadly speaking, a perfect plug must possess the following fundamental properties:—

(a) Freedom from short circuit.

(b) Resistance to electrical leakage and puncture.

(c) Gas tightness.

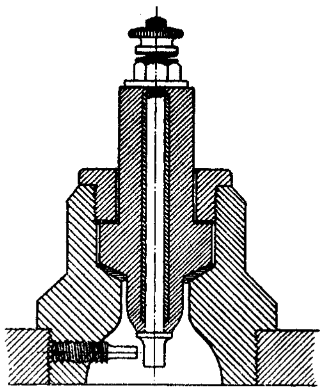


Fig. 7.

(d) Immunity from pre-ignition and possession of unoxidisable electrodes suited to particular engine requirements.

(e) Durability.

(f) Suitable "reach" and length of barrel.

(g) Resistance to rust or corrosion.

These properties, which are by no means arranged in the order of their importance, will be very briefly discussed.

(a) *Freedom from Short Circuit.*—This is attained by keeping the electrodes the correct distance apart and by proportioning the electrodes and insulator so that they reach a temperature just high enough to burn off the deposit due to too rich a mixture or excess of oil, but not high enough to cause pre-ignition.

It is interesting to record that one plug has been advertised with an arrangement for pushing down and twisting round the central electrode in order to scrape off foul accumulations.

(b) *Resistance to Electrical Leakage and Puncture.*—This property is acquired by using only the finest materials for insulators, and designing them so that the barrier is of sufficient thickness to ensure an ample safety factor and in order that the leakage or creeping surface may be as long as possible.

(c) *Gas Tightness.*—Plugs, particularly those used on modern high efficiency engines, should be capable of withstanding high pressures at various temperatures. Gas leakage is attended not only by sooting and loss of efficiency, but by excessive heating, which may eventually cause the fusing of the electrodes and destruction of the insulator.

It is indeed a very difficult matter to make a plug perfectly gas-tight under the varying conditions of temperature and pressure, as, not only has the structure to bear the severe mechanical buffeting, but the insulator and shell expand and contract independently, and the gas-tight medium effecting their union must allow for this.

Different makers have solved the problem in different ways, and a number of typical designs are described and discussed in Section (6).

(d) *Immunity from Pre-Ignition and Unoxidisability of Electrodes suited to Engine Requirements.*—Pre-ignition troubles are avoided by so designing the electrodes and insulators that, in operation, they do not attain too high a temperature, and this point, together with the question of the form of the electrodes, is discussed in detail in Sections (4) and (5).

(e) *Durability.*—Durability in service is principally guaranteed by the careful selection of materials, and by so designing the components that fragility, due to insufficient section or undue overhang, is avoided. The problem of the unequal expansion of insulator and body is a very serious one, and all these points are dealt with at greater length in Sections (4), (5) and (6).

(f) *Suitable "Reach" and Length of Barrel.*—The ideal spot at which the ignition of a charge should be started is, in certain cases, the centre of the combustion chamber, as this provides for the shortest possible travel of the explosive wave and hence effects complete combustion in the most expeditious manner. The worst position for the plug electrodes from this standpoint is in a pocket, formed, for example, by the valve cap. For good results the business end of the plug must therefore protrude reasonably into the combustion chamber; in other words, the "reach" must be adequate but not excessive, or heat conduction will be impaired and pre-ignition result.

At the present time the depth of the plug holes is by no means standardized, and this is another feature which necessitates special plugs for particular engines. The length of the barrel must be amply sufficient to enable an ordinary spanner to be conveniently used, but occasionally, in special cases, considerations of overhead space have a limiting bearing upon this matter.

(g) *Resistance to Rust or Corrosion.*—The resistance of the plug body to rust or corrosion is of some importance, as under the effect of high temperatures the gland nuts are only too apt to become immovably attached to the shells, and, moreover, the plug threads may become corroded to the engine with exasperating results in time of ignition trouble. One plug is provided with a brass body, and from the points of view of resistance to corrosion and of heat dissipation this is to be commended.

We have thus briefly reviewed the various attributes of the perfect plug, and the conviction is borne in upon the author that some day engine design will be so standardized as to eliminate the necessity for such multifarious designs.

(4) Electrodes.

The electrodes provided on the various makes of plugs are exceedingly diverse in their form, and, indeed, there is no doubt that many are quite unnecessarily complex. It is a significant fact that the vast majority of successful plugs in use are fitted with electrodes of simple design, and it is only occasionally that the more elaborate varieties are met with in practice.

In the first place, the electrodes must be constructed of a material which will not fuse or corrode, and pure nickel is the metal which has been generally chosen as the most suitable. Even when nickel is used the cross section of the electrodes must not be too small, or they will become incandescent, and thus cause pre-ignition and eventually destructive oxidation. This was the cause of many of the early failures of the designs of plugs, as the central stem was often a thin wire. Modern practice demands a substantial rod; one of the fundamental requirements of the sparking points is that they should be massive and not unduly isolated from the cooler surfaces, so that the heat is rapidly conducted away. This is most necessary in the case of two-stroke air-cooled engines. There is, of course, a limit to the mass of the electrodes, for if they have too great a capacity for heat, they undoubtedly rob the spark of a portion of its heat energy—an eventuality which must be guarded against—and very cool points are also liable to sooty

CURVES SHOWING RELATION BETWEEN SPARKING DISTANCES BETWEEN POINTS AND SPHERES.
TEST MADE WITH TYPE Z.E.I. MAGNETO.

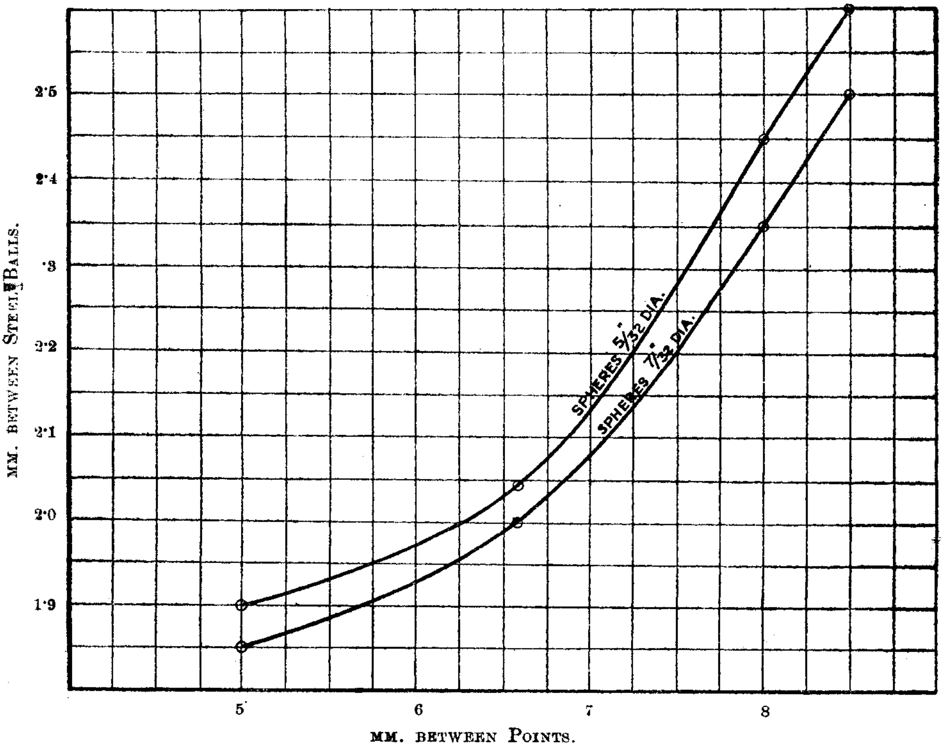


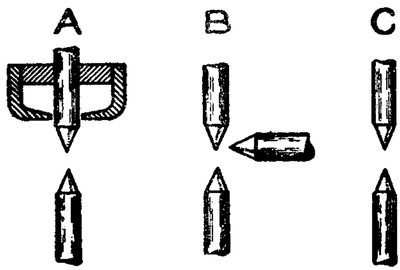
FIG. 8.

accumulations. Thin wires terminating in spheres represent bad design, because the spheres get very hot and the heat cannot escape readily enough by way of the wire stems.

The electrodes should be designed to make the passage of the spark easy, and from this standpoint sharp points would be chosen. To illustrate this, Fig. 8 gives curves which show the voltages required to leap corresponding gaps between points and spheres. The disposition of the electrodes with regard to adjacent metal is not without effect upon the ease of sparking, and the extreme case is illustrated in the familiar three-point arrangement of electrodes widely used in magneto testing. It is well known that the addition of a third point adjacent to one of the active electrodes very considerably lowers the voltage required to cause a spark to leap the gap.

To illustrate in a general way how the characteristics of a gap depend on the disposition of the electrodes, Fig. 9 shows the

ELECTRODES.



MAX. VOLTAGE.	GAP.		
	MM.	MM.	MM.
7000	7·0	6·2	4·0
6000	6·0	5·5	3·1
5000	5·0	4·8	2·3
4000	4·0	4·0	1·5

A. Nickel Points and Insulated Bowl-shaped Aux. Electrode.
B. Nickel Points and adjacent Insulated Nickel Point.
C. Nickel Points.

FIG. 9.

voltage required to leap various gaps between three special sets of nickel-pointed electrodes of different forms.

The practical objection to sharp points is, of course, that they burn away too readily, and thin particles of metal are apt to become detached from the points under the action of the arc, and these particles may bridge the spark gap. The firing pole of the present day only takes a form such as that of a knife-edge.

It is interesting to note that with a constant voltage applied between electrodes of exactly the same form, tungsten favours rather a longer arc than nickel, and the former metal is also less noticeably oxidised.

Experimenting on explosive mixtures of methane and coal gas with air at low direct and alternating voltages, Thornton has shown that nickel electrodes require less energetic sparks to ignite the gas than iron or copper electrodes. It may be, therefore, that ignition is affected by the nature of the incandescent matter passing between the poles.

Platinum electrodes are occasionally used in plugs, and an example is illustrated in Fig. 10, Plate XXXIX. In this plug the platinum central electrode is embedded in the porcelain insulator, its tip coming flush with the end of the insulator cone. In this type of embedded electrode it is essential that the point should not overheat, as this would almost certainly result in the fracture of the insulator.

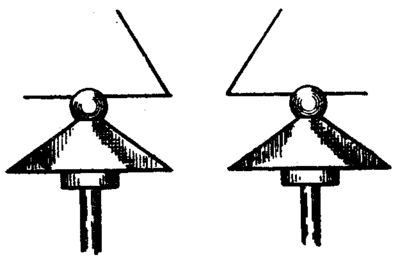
A number of different plug electrodes are illustrated in Fig. 11, Plate XXXIX., and Figs. 12 and 13, Plate XL., and these are fairly representative of those met with in this country and in America. Some engines operate best with one kind of plug electrode, others with another kind, and this largely accounts for the many different designs. It is the author's view that generally a multipoint plug is to be preferred to one of the single point variety, as the gaps of the former usually require less frequent adjustment than those of the latter, and with a multipoint plug it does not matter if the active gap is momentarily rendered impassable on account of oil splashes, as the spark has alternative firing gaps.

The Bosch plug, with its much discussed split central pin, is shown on the extreme right of Fig. 11. The principal advantage possessed by this plug is that the four insulated points, united inside the body, extend unbroken right through the plug to the outer air, and thus heat conduction is well provided for. It is said that the split electrodes were liable to vibrate off and drop into the engine cylinders, and incidentally the plugs were not always gas-tight. A later pattern of Bosch plug was fitted with a cylindrical central electrode and two fan-like body electrodes.

In oily engines it is a distinct advantage to arrange the electrodes so that their firing points are above their lowest points. By this means any oil that may be deposited runs away from the points and drips off without adversely affecting the operation of the plug. The electrode, fastened at both ends, illustrated on the left-hand side of Fig. 12, Plate XL., will not be twisted or broken in cleaning, and the third plug from the left on the same Fig. possesses rod and ring electrodes—a type of gap to be recommended on account of uniform electrical characteristics under various conditions of wave form, etc. The gap on the extreme right of Fig. 12 is very well protected. Fig. 13 shows some further examples of electrode design, the plug illustrated on the extreme right of this figure being of American origin.

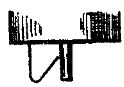
Electrodes arranged as shown in Fig. 14 turn the "Horn-arrester" effect, well known to electrical engineers, to good account.

ELECTRODES.



HORN ARRESTER.

Arc struck between Bends of Copper Horns travels upwards, is drawn out and breaks.



Plug Points **designed** on **this** principle.

FIG. 14.

The arc is struck between the point of the electrode and the side of the central electrode, and then rapidly travels up the electrodes, finally breaking as the gap increases. This movement of the spark is said to produce a scouring effect upon the electrodes, thus keeping them free from carbon deposits.

The generally accepted spark gap for plugs is 0·5 mm., and this should not be greatly exceeded, or undue strain will be put upon the magneto. On the other hand, the gap should not be much smaller if freedom from short circuits is to be guaranteed. Experiment has failed to reveal any appreciable difference in the power developed by an engine on varying the plug gaps over a wide range.

The variation of the electrical conductivity of electrodes with temperature is a point often referred to, but since the available voltage is anything up to 10,000, the variation of the resistance of the electrodes is negligible.

Summing up, the question of electrodes resolves itself broadly into:—

(a) The provision of poles substantial enough to be mechanically robust and to avoid overheating.

(b) The metal should generally be practically pure nickel.

(c) The form of the electrodes should be simple and such as to make the passage of the spark across a 0·5 mm. gap as easy and certain as possible.

(d) The shape should preferably allow oil to drip harmlessly away.

(5) Insulators.

The remarkable severity of the conditions imposed upon sparking plug insulators accounts for the fact that, broadly speaking, there are only three different materials in general use at the present time. They are porcelain, steatite, and mica, and all are closely allied in chemical composition.

The author will consider this phase of the subject from three standpoints: (a) The composition and properties of the insulator; (b) The form of the insulator; (c) Possible future insulators.

(a) *The Composition and Properties of the Insulator.*

Porcelain.—The art of making porcelain is one of the most ancient in existence, and it may be said that the difficulty of manufacture is unity of two earthy substances, one fusible and the other infusible, at a given temperature. Thus, on making an intimate mixture of the earths in question and firing the mass, an impervious translucent product is obtained.

The infusible earth is kaolin (hydrated aluminium silicate), and the flux, or fusible portion, is usually felspar (a trisilicate of aluminium). Small proportions of flint and magnesium silicate are sometimes added. The kilned product is coated with glaze, sometimes by dipping into water in which a very finely pulverised glaze is in suspension, and drying and firing at a higher temperature than before. The insulators are allowed to cool very slowly, and it is this cooling which very largely determines the brittleness of the product.

The glaze may be composed of borax, lead, flint and China-clay, or of quartz, kaolin, lime and porcelain. It forms a kind of glass by its fusion, and envelopes the insulator, eliminating all chance of porosity and ensuring ease of cleaning.

The permanence of the glaze at high temperatures is of the utmost importance, as should it be destroyed the insulator will suffer severely.

Some of the best quality porcelain insulators for plugs have hitherto been manufactured in France, as clays particularly suited for the purpose are found there.

Porcelain has a very high electrical strength, it is perfectly weather-proof, is gas-tight, and its smooth surface favours cleanliness in service.

Mechanically it is, of course, somewhat brittle, and unless the design of the plug is most carefully thought out and the workmanship is of a sufficiently high order, there is always a liability to fracture on account of unequal expansion. If these details are successfully attended to, however, and if the right porcelain is used, there is no great danger of disintegration at the highest temperatures met with. The insulator is found to be inert, and under ordinary conditions it consistently retains its electrical properties and gas-tightness.

Mica is rather a better dielectric than porcelain, and porcelain is better than steatite, but all are equal to meeting ordinary plug dielectric requirements, if properly selected.

The dielectric resistance of all these insulators diminishes with rising temperature, and this is a matter for very serious consideration, particularly in conjunction with the high temperatures met with in the latest aeroplane engines. The resistance of the best insulators may be relied upon at all temperatures up to about 350° C.*

Steatite.—Steatite is a natural product, being a mineral widely distributed in nature and closely allied to soapstone or talc. It is a tetrasilicate of magnesium ($Mg_3\ Si_4\ O_{12}$), it may be readily machined in its natural state, and when turned up to shape may be hardened by heating without any distortion occurring.

* Interesting references to this phase of t e subject may be found in an article by Mr. Stephenson, and a letter from the Lodge Sparking Company, Limited, which appeared in the issues of the "Motor Cycle," dated October the 18th and November the 1st, 1917, respectively.

It has long been used as an electrical insulator for operation at high temperatures in such devices as arc lamps and radiators, but the particular defect which has to be overcome in its application to plug manufacture is its porosity. Unfortunately, prior to the war, the production of steatite plug insulators was largely monopolised by the Germans, and the problem of suitably glazing the material, which is naturally more porous than porcelain, was left in their hands.

The most interesting variety of steatite is known as "reconstructed" steatite, and this is made by moulding up the crushed mineral mixed with some suitable fire-proof cement, which functions as a binder.

It is said that the glaze met with on steatite plug insulators is liable to fuse and run, and so give rise to porosity, but this has not been the author's experience, as he has found steatite to be equal to porcelain, and, moreover, it is apparently tougher mechanically. Steatite, like porcelain, withstands considerable quantities of oil and sooty deposits without causing misfiring, and it resists fracture under varying temperature conditions to about the same extent as porcelain.

Mica.—Mica, like steatite, is a natural product, and of all minerals it is perhaps the most interesting on account of its extraordinary chemical, electrical, optical, and mechanical peculiarities. There are many varieties of mica, but all are, from a chemical standpoint, silicates of alumina and alkalis, and sometimes iron oxide and magnesia occur in combination.

Mica is exceedingly widely distributed, but localities in which deposits occur in sheets large enough to be of value to commerce are limited in number. Most of the mica comes from India, America and Canada, and the variety known as ruby mica is commonly used in the construction of plug insulators. Care must be exercised when selecting mica that it is as free as possible from impurities, such as clay or iron oxide.

The laminar structure of mica is very well known, and the consequent lack of lateral cohesion is one of its outstanding characteristics. The mineral cannot be usefully fused, moulded or brought into solution, and therefore insulators must be built up of laminæ, held rigidly together by some clamping arrangement.

Mica is not in any way acted upon by the combustion gases, it is quite unaffected by ordinary changes of temperature, and will not crack in service, as even the very best porcelain or steatite insulators are liable to do. Under the action of very high temperature (450° C.) mica blisters and tends to disintegrate along its planes of cleavage, but this deterioration is reduced to a minimum in plug insulators as the material is under very considerable pressure.

A properly constructed mica insulator is not at all fragile, but it requires more frequent and careful cleaning than porcelain or steatite. The layers are, of course, separated by infinitely thin strata of air, and the insulator therefore offers no greater electrical resistance parallel to its laminæ than an air gap. It is of vital importance that the pressure on the laminations should be sufficient to keep them close enough together to absolutely exclude oil or dirt, which would speedily carbonize and form a leakage path for the spark.

Mica is a very poor conductor of heat, and consequently in designing mica insulated plugs, special attention has to be devoted to the cooling of the electrodes.

(b) *The Form of the Insulator.*—The form of plug insulators is of as much importance as the material of which they are constructed, as however perfect the barrier may be in its dielectric nature, the plug will be useless if the leakage surfaces are not properly arranged, and the insulator will be unduly fragile if particular care is not exercised to obviate this defect. In designing insulators of porcelain and steatite, not only must the adequacy of the sections be ensured, but it is also imperative, if freedom from cracking is to be obtained, that the design should be symmetrical. This point is well illustrated by the two-pole plug insulator shown in Fig. 15. Here, by using concentric electrodes, the makers have avoided the more usual unsymmetrical arrangement of two parallel electrodes.

The function of the insulator is to isolate and support the central electrode. A sufficient length of insulator must protrude upwards above the top of the shell to safely insulate the plug terminal, and the lower end must ensure that the spark occurs only at the electrode points. The middle portion or shoulder provides the means of clamping the insulator.

So long as the upper end of the insulator extends beyond the top of the shell by a sufficient amount to prevent surface leakage, and its proportions guarantee mechanical strength, there is no special difficulty in design.

The length of the insulator clamped between the shell members must be kept as short as possible, consistent with mechanical considerations, so as to reduce to a minimum the difference in the lineal expansions of insulator and shell. This portion of the insulator receives more detailed attention in Section 6.

The lower end of the insulator which protects the firing point of the central electrode requires very careful consideration, as this is one of the most vital parts of the plug. A long insulation or leakage surface must be provided, but at the same time the

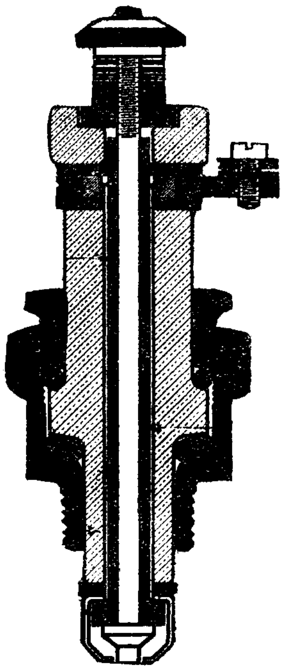


FIG. 15.

petticoat must not be so exposed as to become incandescent and produce pre-ignition. Fig. 27 shows a plug, the insulator of which is well protected.

In practice the lower end of the insulator usually forms either a petticoat or cone around the central electrode, and the threaded portion of the plug, sometimes overhanging inwards somewhat at its extremity, shields the porcelain from too intimate contact with the explosion flame.

A plug in which the cone or petticoat is too short will be liable to short circuit, and one with extended but unprotected insulation will cause pre-ignition, and probably quickly fracture in service. The successful plug must, as mentioned above, possess ample insulation surface which must operate at such a temperature that sooty deposits are just burnt off without danger of producing pre-ignition.

Some plugs have been fitted with conical tubes at their mouths with the object of causing any engine deposit to occur on the inside of the insulator petticoat, and so keep the outer surface clean.

Porcelain or steatite insulators, though chiefly of the single type, are often met with in multiple form.

A well-known make of plug is provided with a porcelain insulator divided into three sections. By this means the temperature differences between the ends of the porcelain are minimised, although the construction of the plug is necessarily somewhat complicated. A section of a portion of this ingenious plug is shown in Fig. 20, from which the principle of the construction can be seen. The insulation of this plug is assured by lining the inside of the body with mica sheets.

The multi-porcelain plug can be dismantled, but, naturally, it cannot be re-assembled with the same ease as the single porcelain type. It appeals to the author as representing a successful effort to minimise the effects of unequal expansion.

Turning now to the form of mica insulators, it is clear that the material is subject to certain limitations which necessitate the use of plug bodies of suitable design. The central electrode must be wrapped with extremely thin sheets of well-chosen mica (from 0·0005 in. to 0·001 in. thick, depending on the electrode diameter), otherwise the mica will be damaged in the process of wrapping, with resultant loss of insulating value. The wrapping is held in position by mica washers which are threaded over the stem and insulation, and these washers are securely clamped together. As mentioned above, they have a purely mechanical function, and must not be relied upon to insulate the electrode. They serve to secure the wrapped insulation about the electrode, to locate the electrode, and to provide the gas-tight joint between insulator and shell. For this last purpose the mineral is admirably suited, as it is able to withstand almost unlimited pressure at right angles to its laminæ. It is essential that the shell seatings should be carefully machined so as to provide properly smooth and flat faces to evenly distribute the pressure over the surface of the mica.

Some of the best mica plugs are provided with a means of securing the gland nut, which is otherwise liable to work loose in operation and thus affect the gas tightness.

There is one other point about mica, namely, that should a flake or two become detached and fall within the cylinder it will do no damage to the walls or piston.

(c) *Possible Future Insulators.*—The author cannot dismiss the subject of insulation without reference to the possibilities of quartz

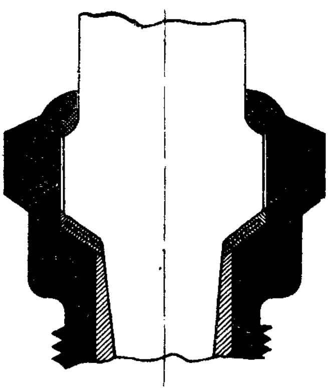


FIG. 16.

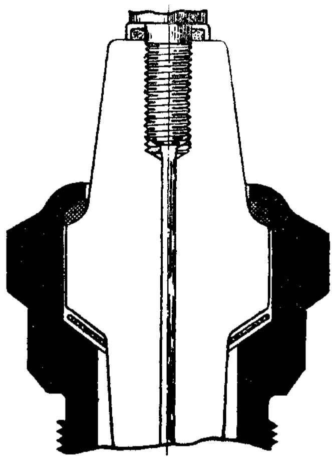


FIG. 17.

or silica as a plug insulator. Quartz insulated plugs are not altogether unknown, but they are by no means common. From the point of view of complete indifference to extreme changes of temperature quartz is ideal, and as an electric insulator it is quite satisfactory, maintaining its strength as a dielectric with increase of temperature. The main difficulty is, that it cannot at the moment be very readily worked and produced to accurate dimensions. The art of working silica has made very rapid strides in recent years, and it is not too much to hope that before long this product will be available for plug insulators.

(6) The Problem of Gas Tightness.

This is a problem in the solution of which the plug manufacturer has displayed the utmost ingenuity, and the variety of methods adopted is very great. The expansion co-efficient of the insulator is considerably less than that of the metal shell, and consequently under varying temperature the two expand and contract independently. Not only has the sealing to remain perfect under these conditions, but also in no circumstances must the insulator be clamped so tightly or rigidly as to result in fracture.

Fig. 16 illustrates the method of sealing adopted in a certain single porcelain plug, and it will be seen that the body of the porce-

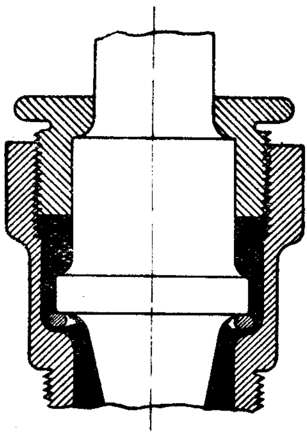


Fig. 18.

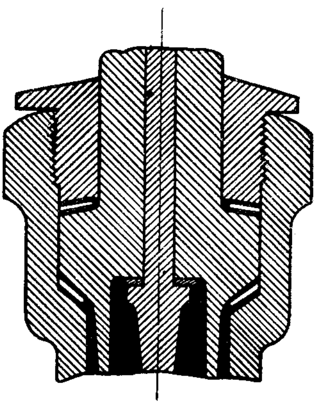


Fig. 19.

lain is gripped above and below by the metal shell, the top of which has been pressed over after the insulator has been inserted. The two gaskets interposed between the metal and the porcelain at the top and bottom respectively are relied upon to make gas-tight joints. It is claimed for this plug that the manufacturing process is such that the pressure is very evenly distributed. The central electrode (not shown) is cemented in position.

In Fig. 17 a similar plug is illustrated, but in this instance the central electrode is screwed and cemented in position in the porcelain.

Fig. 18 indicates the construction of a plug in which the pressure on the insulator is obtained by screwing in the gland nut at the top of the shell. By this means the porcelain is pressed down upon the gasket ring shown between the bottom of the ridge of the

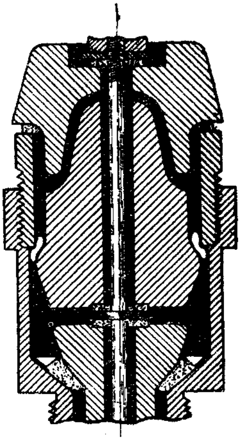


FIG. 20.

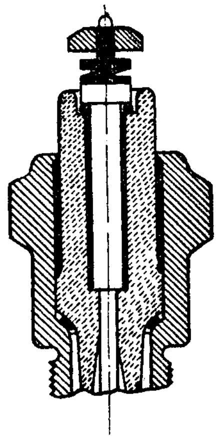


FIG. 21.

insulator and the shell. This plug, in common with others of similar pattern, possesses the advantage that it may be readily dismantled for cleaning.

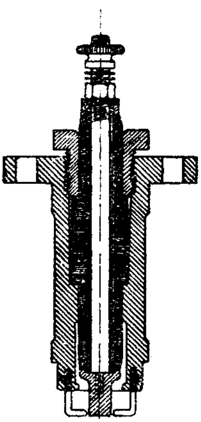


FIG. 22.

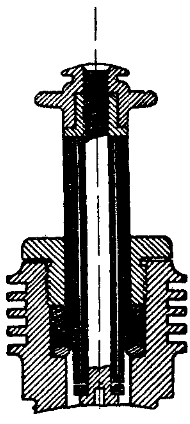


FIG. 23.

Fig. 19 shows a somewhat similar arrangement, but in this case two gaskets are provided.

Fig. 20 illustrates a very popular multiple porcelain plug. The three separate insulators make gasket joints at three points, as shown, and the central electrode is similarly sealed at the top and bottom.

Another familiar plug is shown in Fig. 21, where it will be seen that the single steatite or porcelain insulator is united to the metal shell and central electrode by means of a special enamel.

A large gas engine plug is shown in Fig. 22; here the central insulator is made up of mica washers clamped rigidly together on the central electrode which is of mild steel with a nickel tip, and previously wrapped round with sheet mica. A gland nut clamps

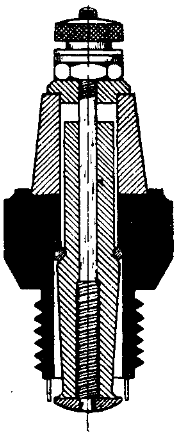


FIG. 24.

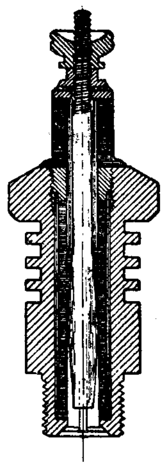


FIG. 25.

the complete insulator down upon the ledge provided in the cavity of the body, much in the same way as is usual with porcelain insulators, only the elasticity of the mica is such that the gasket may be dispensed with.

Another mica plug is shown in Fig. 23. The main core of the central insulator is built up of mica washers and provided with square shoulders which are clamped between gaskets in the manner shown. A baffle plate (not shown) is provided near the lower end of the plug which prevents undue splashing of oil upon the mica. The central electrode is wrapped with sheet mica, and the sealing of the joint is ensured by the clamping action secured by the nut on the upper end.

A third mica insulated plug is indicated in Fig. 24, from which it will be seen that the mica wrapping is rather differently arranged. The mica washers which occupy the lower cavity of the shell are rigidly compressed by the downward pressure of the nut at the top, and the copper central electrode is so shaped that when drawn upwards by the tension of the nut near its upper extremity it makes a particularly good conical joint with the mica washers constituting the body of the insulator.

A novel plug is illustrated in Fig. 25, which shows that the usual custom of clamping the porcelain between portions of the shell has been reversed. It will be observed that there are two

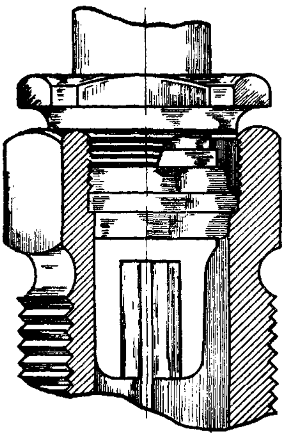


FIG. 26.

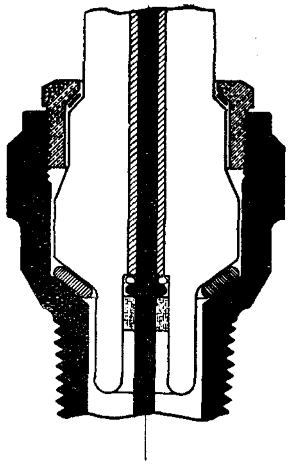


FIG. 27.

insulators, a central porcelain and a sleeve. The shell is clamped between these two insulators by means of the stout central electrode which is threaded to accommodate a clamping nut at the top.

An all-metal packing is illustrated in Fig. 26, from which it will be seen that a metal packing collar is forced over each of the obtuse cones formed by accurately grinding the shoulder of the porcelain, and the flanges of the collars coming together form a rigid shoulder, which is securely gripped by the plug body. It is claimed that the expansion co-efficient of the metal used is the same as that of the porcelain, and this, together with the advantage of the ground joint, is said to eliminate all compression leakage.

The illustrations selected by no means exhaust the available examples, but they are typical of the rest, and serve to indicate the manner in which gas tightness is aimed at in practice, and incidentally the remarkable ingenuity displayed by the plug designers is emphasized.

Reviewing the various types it may be said that the varieties which cannot be dismantled have the advantage that the manufacturers' pressure and skill of assembly are life-long assets to the well-being of the plug, but, of course, the cleaning of the insulator is not an easy matter. On the other hand, in gaining ease of cleaning the type which may be dismantled usually requires intelligent and careful re-assembly in order that long life and efficiency may be ensured. Considering all things, it seems that a single gasket is hardly preferable to two or even three, but there must of course be a limit to the number of gaskets in order that undue cushioning and resultant lack of rigidity may be avoided.

As previously stated, the different rates of expansion of the body and insulator make it advisable to keep the length of insulator clamped between the gaskets as small as possible, but this length must not be unduly small, or else the insulator will too easily fracture as a result of a lateral blow on account of the large leverage.

In the permanently assembled class, the type in which the insulator and metal parts are united by enamel makes its appeal on the grounds of mechanical simplicity, and experience with plugs of this pattern has proved the construction to be sound and efficient.

In the mica class it is noteworthy that it is not only necessary to make gas-tight joints between the insulator and the shell, but the structure of the insulator itself must also be such that pressure renders it impervious to gas under all conditions.

The author believes that the problem of avoiding compression leakage is the most difficult one which has to be faced by the plug manufacturers. Great as have been their efforts in the past to achieve this end, and bearing in mind the excellence of the performance of plugs of certain well-known makes, it may yet be said that this problem remains a real difficulty. Present day engine pressures and temperatures call for continued effort on the part of the plug makers just as much as they reflect credit upon the designers of those plugs which are giving good service in this respect.

(7) Special Plugs.

The foregoing has been principally devoted to matters relating to sparking plugs of ordinary design, such as are commonly met with in every day use, but in the present section, attention is directed to one or two plugs which, for certain reasons, may be regarded as extraordinary.

Special plugs have already been mentioned incidentally in the preceding pages, and there is no lack of further examples, as inventive genius has produced an abundance of patents covering the manufacture of plugs, embracing outstanding peculiarities.

Fig. 28 shows a plug, in which the insulator has been reinforced by means of a metal core provided with arms extending in a radial manner. It is suggested that the strengthening core should be em-

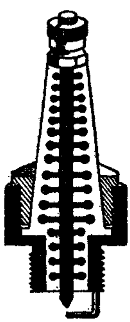


Fig. 28.

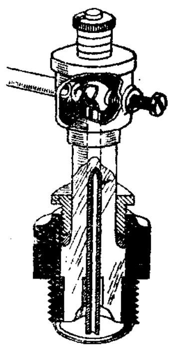


Fig. 30.

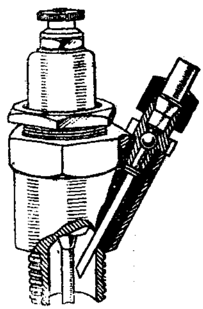


Fig. 31.

bedded in steatite or porcelain, but the practicability of this proposition seems to be rather remote.

Fig. 29, Plate XLI., shows a plug in which a gap arranged in series with the firing gap indicates to the observer whether the plug is operating or not. It is of interest to note, in connection with this plug, that, although the presence of the spark in the observation gap indicates that high tension current is being supplied to the plug, it does not convey any information as to whether the firing gap is short circuited or operating normally.

In Fig. 30 a plug is illustrated in which the central electrode is hollow. Arrangement is made for a part of the explosive charge to be drawn from the induction pipe into the cylinder, *viâ* the central electrode of the plug, and there is no doubt that the gas rushing inwards would tend to cleanse the earthed electrode. The device operates something like an old automatic inlet valve.

Another self-cleaning plug is shown in Fig. 31. In the case of a four-cylinder engine the side tubes of the four plugs are connected in a distributor tapped into the induction pipe, and by this means some of the charge is drawn into the cylinders by way of these tubes on each induction stroke. From the point of view of certainty of ignition the introduction of the charge in this manner is a good feature, and, undoubtedly, there must be quite an appreciable scouring effect upon the central electrode of the plug. It will be noticed that a ball valve is fitted to each plug.

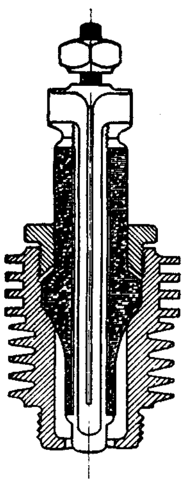


Fig. 32.

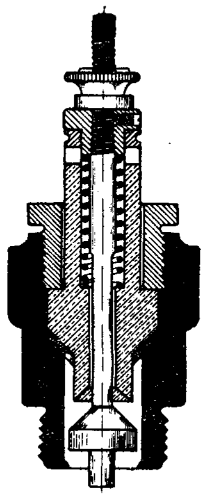


Fig. 33.

An air-cooled sparking plug is shown in Fig. 32, from which it will be seen that the shell is provided with radiating fins, and in addition a tubular central electrode of large diameter is utilised. The plug is screwed in so that one of the conical openings in the upper end of the hollow electrode faces in the direction of motion, and thus a certain amount of air is induced to pass down on one side of the central baffle and up the other side. This is a very ingenious attempt to cool the plug, and it may be that if engine conditions get very much more severe, some such arrangement as this will eventually have to be adopted.

Another air-cooled plug is illustrated in Fig. 33. In this instance the central electrode operates as a valve and is displaced downwards as a result of the vacuum produced in the cylinder on each induction stroke, and thus cool air rushes through the air holes in the upper part of the sides of the plug, and sweeping past the stem of the central electrode, prevents it from attaining too high a temperature.

Yet another air-cooled plug is shown in Fig. 34. In this case the mechanism is hand operated, and it is said that the plug was first produced as a means of de-carbonising two-stroke engine plug points in operation. Whilst coasting down hill the points may be cooled and the gap cleared by permitting the engine to

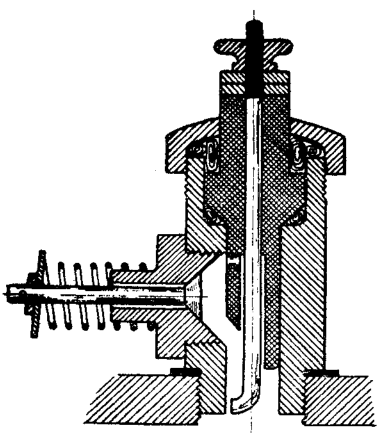


FIG. 34.

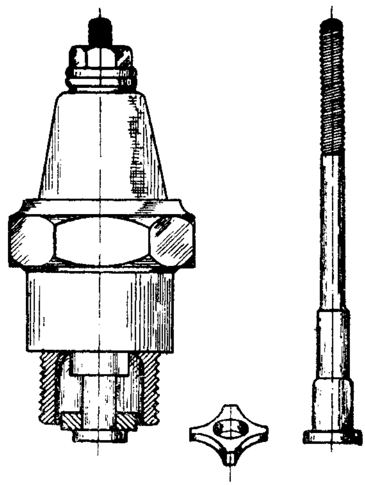


FIG. 35.

run with the throttle closed, and opening the valve at the side of the plug body.

A self-cleaning plug is shown in Fig. 35, which illustrates the use of a loose star-shaped disc which is free to revolve at the lower end of the central stem. Whilst the engine is operating this disc will undoubtedly be in a state of continuous motion, and there seems very little chance of sooting up occurring under these conditions.

One other plug is illustrated, not particularly on account of any peculiarities in design, but more because of special attachments.

Fig. 36, Plate XLI., illustrates a well-known American plug in which a moulded composition protector has been screwed to the plug bushing in order to perfect the high tension connection.

A useful suggestion for protecting plug points from excessive oiling is shown in Fig. 37, Plate XLII.

A recent patent discloses a plug design which incorporates a priming cup through which, on depressing the electrode against the action of a spring, the fuel passes to the interior of the plug.

Another invention relates to a plug in which the insulation is provided by coating the interior and a portion of the exterior of the hollow shell with vitreous enamel. This is an interesting departure, because, if the enamel does not chip off in practice the idea of a plug without a separate insulator is rather alluring.

The examples which have been mentioned are sufficient to illustrate the genius which has been displayed in the devising of means of overcoming the inherent defects associated with plug design, and the persevering tenacity with which the production of the perfect plug has been aimed at.

The question of the design of plug terminals and connectors has not been entered into, as it is one which presents no particular points of difficulty or interest, and may be dismissed with a mere reference to an interesting heat radiating terminal which was provided with fins recently put forward.

(8) Problems still Requiring Attention.

The study of sparking plugs of the past, present and future, leads to the realization of the existence of problems yet to be solved and difficulties still encountered. Engine makers tell us that the perfect plug has yet to be produced, but this is not because there has been any lack of concentration or any dearth of enthusiasm amongst the plug producers, but rather on account of the many difficulties which have to be overcome.

As has already been pointed out, the outstanding difficulties are (1) to ensure gas tightness, (2) to procure insulators immune from electrical and mechanical failure under varying temperature, and (3) to prevent fusion of the electrodes. There is no doubt that the present national emergency has done much to hasten the attainment of many engineering ideals, and the plug industry has by no means occupied a back place in this respect. It remains now for the plug designers, assisted by the advancing knowledge of the production of insulators and the co-operation of the engine builders, to render more uniform that success which already crowns the efforts of some of them.

In conclusion, the author wishes to acknowledge his indebtedness to Mr. A. P. Young, A.M.I.E.E., A.I.A.E., for much valuable assistance, and the permission to make free use of one of his unpublished articles entitled "The Process of Ignition." The author also thanks Mr. H. P. Wiggins, A.M.I.E.E., for information regarding mica, and finally gratefully acknowledges the courtesy of the British Thomson-Houston Company in permitting the publication of certain results arrived at in their experimental laboratories.

FIG. 10.

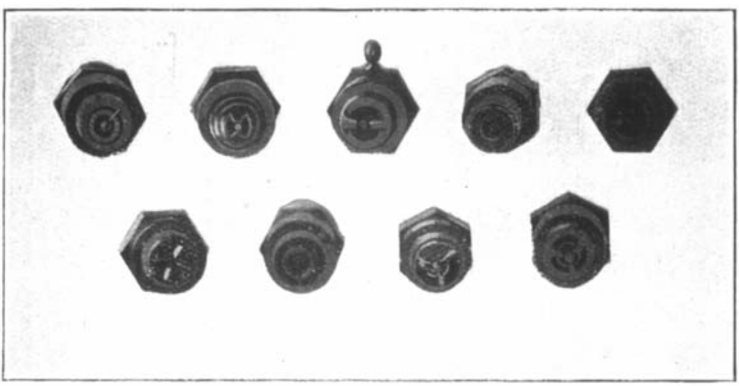


FIG. 11.

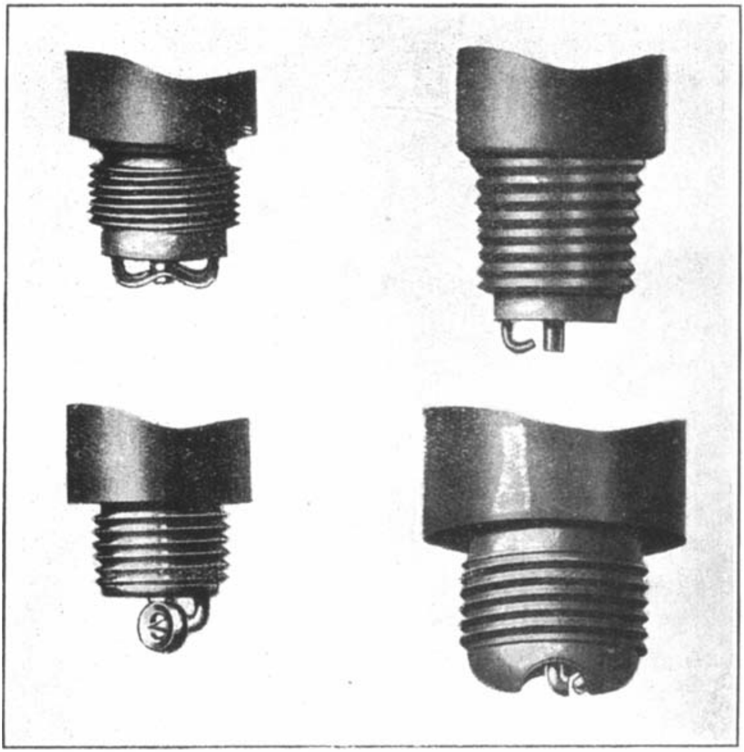


FIG. 12.

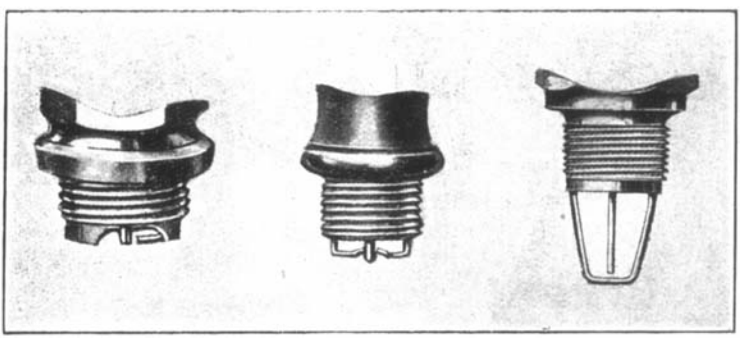


FIG. 13.

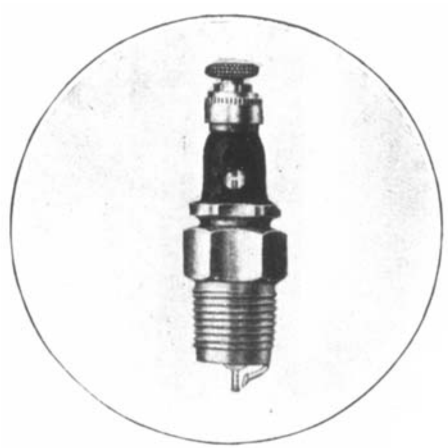


FIG. 29.

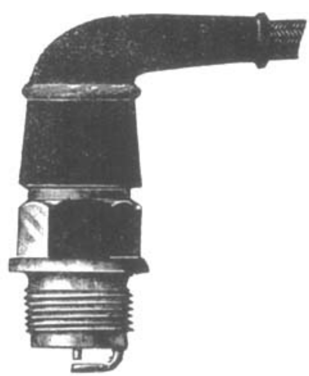


FIG. 36

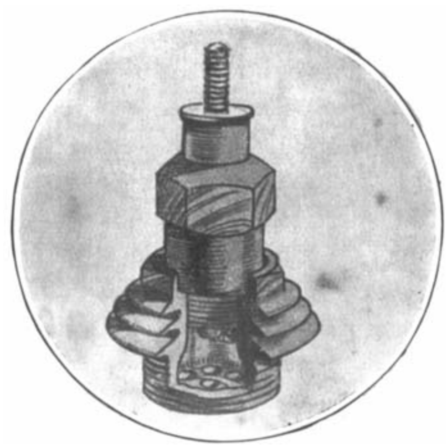


Fig. 37.